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SYNTHESIS OF H_2 IN DIRTY ICE MANTLES BY FAST ION ENERGY LOSS: NEW EXPERIMENTAL RESULTS INCREASE THE RELEVANCE OF THIS MECHANISM

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Abstract

We point out that recent experimental results obtained at Bell Laboratories support the importance of H_2 production in molecular clouds by cosmic ray bombardment of the mantles of grains.

1. INTRODUCTION

H_2 is one of the most important interstellar molecules, both because of its abundance and because of the central role played in the development of the chemistry, which occurs in both diffuse and in dense clouds. H_2 is, in fact, the molecule which, when ionized either by UV photons or by cosmic rays, triggers the gas phase ion-molecule reaction chains; for this reason it is sometimes emphatically called the "seminal" molecule. This fact makes molecular hydrogen also relevant for the collapse and the fragmentation of interstellar clouds, and hence for the formation of stars and the structure and dynamics of galaxies.

It has long been recognized that radiative association of two hydrogen atoms in the gas phase cannot be responsible for the presence of interstellar H_2: the molecule is formed in a highly excited state and it is not able to emit a photon carrying the formation energy before dissociating. A third body is therefore required to absorb the formation energy. In interstellar conditions, the third body can only be a grain, acting as a catalyst.

2. RECOMBINATION OF H ATOMS ON GRAINS

The mechanism accepted for many years is the recombination of hydrogen atoms adsorbed on grain surfaces. Two atoms stick on a grain and, if they are mobile enough, can encounter each other, before evaporating, and form an H_2 molecule. This has been treated by many authors and, in particular, by

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Hollenbach and Salpeter (1971).

Hollenbach and Salpeter treated crystalline grains, solids with periodic structures in which the wave packet describing an adsorbed atom spreads quickly, assuring the required mobility. The process gives almost equal probability of finding the atom in any suitable adsorption site. In these conditions, the temperature independent rate R of H_2 formation is

$$R \sim 10^{-13} cm^{-3} s^{-1}$$

Smoluchowski (1983) questioned the choice of a crystalline structure for interstellar grains and considered the formation of H_2 on amorphous surfaces. This is, in fact, likely to be the most suitable structure of grain mantles in dense molecular clouds.

Amorphous ice differs from crystalline ice in its lack of periodicity in the distribution of molecules and of adsorption sites. In such conditions Smoluchowski showed that, because of the non-periodic spacing of potential wells, the wave packet describing the adsorbed atom quickly becomes localized into the deepest traps and, therefore, becomes almost immobile. Smoluchowski evaluated the production rate of H_2 as a function of the grain temperature and the density of atomic and molecular hydrogen in the gas phase.

A general feature of Smoluchowski's results is that the rate of formation of H_2 is orders of magnitude lower than that obtained considering crystalline ice, especially at $T < 18K$. These new results may render other processes competitive in producing interstellar H_2.

3. H_2 PRODUCTION BY COSMIC RAYS

In a recent paper (Pirranello and Averna, 1988) considered as an alternative process the production of H_2 in molecular clouds by cosmic ray bombardment of icy mantles on grains (as already suggested by Pirranello, 1987). The laboratory results of Brown et al. (1982) were used. Brown et al. found that, for H_2O irradiated by MeV helium ions, H_2 molecules are formed and released into the gas phase. More generally, H_2 is ejected by incident ions from any hydrogen rich frozen gas. For details on the experimental equipment the reader is referred to the paper by Brown et al. (1982).

The formation of molecules different from those originally present in the irradiated layer can be explained by the production of molecular fragments induced by the release of energy of the impinging fast particle. One way of considering the process is in terms of a transiently hot cylinder, initially about 50Å in diameter, that exists around the track of an individual fast ion. Since ice has a relatively low thermal conductivity, energy lost by the ion in the ice layer remains confined around the track for a time long enough to be thermalized. The hot cylinder increases in diameter and decreases in temperature on a time scale of $10^{-11}-10^{-10}$ sec. Molecular fragments that are formed in this high temperature region acquire enough mobility to recombine with different partners, forming new molecules.

The production rate of molecular hydrogen at depth "d", in a dense cloud, per unit volume per second is

$$R(H_2) = 4\pi^2 \int_{a_{min}}^{a_{max}} \int_0^{E_{max}} Y_{H_2}(E')\, n_g \frac{dJ'}{dE'}\, a^2 dE' da \qquad (1)$$

where a = radius of the grain
n_g = size distribution of grains
E' = residual kinetic energy
Y = production yield of H_2 by an ion of energy E'
dJ' / dE' = distorted differential energy spectrum

A Monte Carlo simulation of the interaction between cosmic rays and grain mantles, at various depths in the core of a spherical molecular cloud, has been performed. The simulation has been continued until 40000 ions had hit each grain of the type and size chosen.

Pirranello and Averna used as a model of small molecular clouds one of those built by Boland and de Jong (1984). Their predictions seem in good agreement with observed column densities of several molecular species in L134, L183 and TMC-1. These are hydrostatic, self-gravitating spherical models of small molecular clouds supported against gravity by turbulent and thermal pressure, without internal heat sources. Spherical grains at depths $A > 1$ magnitudes, following the size distribution given by Mathis eta al. (1977), were used. The grains considered by Pirranello and Verna were assumed to be constituted by a refractory core, made of graphite or silicates, with a superimposed dirty ice layer consisting of H_2O, CH_4, NH_3, and CO in the relative abundances 5:3:2:1. For production of H_2 from CH_4 and NH_3 they assumed (there are not yet quantitative measurements of yields for these species) the (very conservative) yields of 3.96 and 4.62 per incident 1.5 MeV He ion. The ratio between the core radius and the mantle thickness has been taken to be about 1.

The cosmic rays were taken to be only low energy proton and helium particles with $E < 1$ GeV (taken from Morfill et al., 1976). These ions are the most abundant and their stopping power "dE/dx" (i.e. the energy lost per unit path length) is larger at these energies.

The energy lost by each ion interacting with the gas inside the cloud, before impinging on the grain, was subtracted from the initial energy. In this way it was possible to obtain, from the differential ion energy spectrum "dJ/dE" of the cosmic rays impinging on the clouds from the outside, the distorted differential energy spectrum "dJ'/dE'" at depth "d" inside the cloud.

The Pirranello and Averna (1988) paper gives the production rate of molecular hydrogen per cubic centimetre per second "R (T_g,d)" as a function of the grain temperature "T_g" and the depth in the core of the cloud. The results show that, especially in the low temperature region ($T < 18K$, the region of interest in the core of dense clouds), cosmic ray bombardment of grain mantles is more efficient in producing H_2 than is the recombination of adsorbed H atoms on the amorphous surface of grains. Only in restricted ranges of temperature is this second mechanism more relevant.

4. NEW EXPERIMENTAL RESULTS AND CONSEQUENCES

Using the same experimental techniques and roughly the same equipment as described in Brown et al. (1982), we have irradiated, with 1.5 MeV helium beams, thin icy films made of H_2O and CD_4 mixed in the gas phase and deposited on a "cold finger" at 9K. Among synthesized molecules are found H_2, HD and D_2.

A preliminary calibration of the mass spectrometer output obtained by means of the Rutherford backscattering technique shows that the yields per impinging particle should be raised by almost two orders of magnitude over those Pirranello and Averna assumed for the mixture of water and methane ice (details of the new experimental results will be presented elsewhere). Scaling the results of the previous Monte Carlo simulation with this difference in the assumed yields would then increase the rates at the various depths in the cloud by roughly two orders of magnitude. This fact gives greater relevance to the process of production of molecular hydrogen by cosmic rays impinging on icy organic grain mantles, especially when compared with the recombination of adsorbed H atoms on grains, even if the mobility of H atoms is not as low as that deduced by Smoluchowski.

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